

Nonlocal Spin Transport in Lateral Spin Valves with Multiple Ferromagnetic Electrodes

Tae-Suk Kim and Hyun-Woo Lee

Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Korea

B. C. Lee

Department of Physics, Inha University, Incheon 402-751, Korea

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We study the nonlocal spin transport in a lateral spin valve with multiple ferromagnetic (FM) electrodes. When two current-injecting and two spin current-detecting electrodes are all ferromagnetic, the number of possible nonlocal spin signal states is four at maximum. In reality, this number is reduced, depending on the inter-probe distance and the relative magnitudes of the spin resistances. Our theoretical results are in agreement with recent experiments of spin injection into an Al island, a carbon nanotube, and graphene.

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I. INTRODUCTION

Spin injection^{1,2} from a ferromagnetic (FM) metal into nonmagnetic (NM) materials (metal, semiconductor, insulator) is very important for device applications and for academic interest. The operation of the spin valve, a hybrid structure of FM metal/NM/FM metal, depends on efficient spin injection from one FM electrode into the NM layer and spin detection in the other FM electrode. Typical examples of a spin valve include giant magnetoresistance (GMR) devices³, magnetic tunnel junctions (MTJ)^{4,5,6}, FM/NM/FM nanopillars⁷, etc. The magnetoresistance has been enhanced up to a few hundred percent in the recent MgO-based MTJs^{8,9} and GMR and MTJ devices are already in commercial markets for magnetic read heads. MgO-based MTJs are now being used for magnetic random access memory devices. However, these *vertical* spin valves have some difficulties in integrating them into semiconductor electronics.

In order to integrate spintronic devices into semiconductor electronics, *lateral* spin valves are more desirable for, e.g., multi terminal devices. Due to the increased distance between terminals in lateral spin valves, the spin signal is more suppressed compared to vertical spin valves. Furthermore, spin injection and detection experiments in the two terminal geometry of lateral spin valves are complicated and obscured by other effects like the anisotropic MR, the anomalous Hall effect, etc. In order to avoid these undesirable effects, a nonlocal spin valve geometry¹ in which the spin current path is spatially separated from the charge current path, was adopted, and spin injection and detection were clearly demonstrated in Al wires¹⁰. The nonlocal spin injection technique was also used to observe^{11,12} the (inverse) spin Hall effect in diffusive nonmagnetic metals (e.g., Pt with a spin diffusion length of 10 nm), which are characterized by a rather strong spin-orbit interaction. In these experiments, the separation of charge and spin currents, as well as efficient spin injection, is essential to observing the Hall voltage

induced by the spin current.

If significant magnetoresistance (MR) or nonlocal spin signals are to be achieved in lateral spin valves, the spin polarized current should be able to pass through the intervening nonmagnetic layer without losing or degrading too much of its spin polarization in the NM layer or at the FM-NM interface. Nonmagnetic materials with long spin diffusion lengths (SDLs) are most desirable and are required for successful operation of lateral spin valves. In this respect, recent experiments of spin injection into carbon systems, carbon nanotube¹³ and graphene^{14,15}, are very intriguing. A large spin polarization and a large SDL are observed in carbon systems. In these experiments, the two voltage probes and the two current probes were all ferromagnetic in contrast to previous experiments. Motivated by these experiments, we study in this work the spin transport in a nonlocal spin valve geometry with four FM electrodes, as shown schematically in Fig. 1, based on the one-dimensional spin drift-diffusion (SDD) equations.

II. FORMALISM: SPIN DRIFT-DIFFUSION EQUATION

Spin transport in spin valves can be understood theoretically based on the spin drift-diffusion (SDD) equations^{1,2}, which are a reduced version of the spin-dependent Boltzmann equation. The SDD equations were shown to be valid when the mean free path is much less than¹⁶ or comparable to¹⁷ the spin diffusion length. The SDL is the length scale over which electrons can preserve their spin information. The finite SDL in the samples is caused by the spin-flip scattering due to the spin-orbit interaction, magnetic impurities, etc. Though the SDD equations are phenomenological, they have been very successful in explaining the main features of experiments qualitatively.

The SDD equations are written down for the spin-dependent electrochemical potential μ_α and an electric

current density j_α . Here, $\alpha = \pm$ represents the spin-up (+) and the spin-down (−) states, respectively. In the one-dimensional device structure, the SDD equations can be written down in a matrix form as

$$\frac{d^2}{dx^2} \begin{pmatrix} \mu_+ \\ \mu_- \end{pmatrix} = \begin{pmatrix} \frac{1}{D_+ \tau_{+-}} & -\frac{1}{D_+ \tau_{+-}} \\ -\frac{1}{D_- \tau_{+-}} & \frac{1}{D_- \tau_{+-}} \end{pmatrix} \begin{pmatrix} \mu_+ \\ \mu_- \end{pmatrix}, \quad (1)$$

$$j_\alpha = \frac{\sigma_\alpha}{e} \frac{d\mu_\alpha}{dx}. \quad (2)$$

Here, D_α is the diffusion constant for spin direction $\alpha = \pm$, and τ_{+-} is the average spin-flip time for an electron from the spin direction + to −. σ_α is the conductivity for electrons with spin α , and e is the absolute value of the electron charge. Analyzing the eigenvalues and the eigenvectors of the matrix in the SDD equation, we can find the general solution of the SDD equations for the electrochemical potential and the corresponding current density¹⁸:

$$\frac{1}{je} \begin{pmatrix} \mu_+ \\ \mu_- \end{pmatrix} = \left[\frac{x}{\sigma} + A \right] \begin{pmatrix} 1 \\ 1 \end{pmatrix} + \frac{B\lambda}{2} e^{-|x|/\lambda} \begin{pmatrix} \sigma_+^{-1} \\ -\sigma_-^{-1} \end{pmatrix} \quad (3)$$

$$\frac{1}{j} \begin{pmatrix} j_+ \\ j_- \end{pmatrix} = \frac{1}{\sigma} \begin{pmatrix} \sigma_+ \\ \sigma_- \end{pmatrix} \pm \frac{B}{2} e^{-|x|/\lambda} \begin{pmatrix} 1 \\ -1 \end{pmatrix}. \quad (4)$$

Here, $\sigma = \sigma_+ + \sigma_-$ is the total conductivity, and A and B are parameters to be determined by the boundary conditions. The total or charge current density is constant and uniform in space: $j = j_+ + j_-$. The spin diffusion length λ is defined by the expression

$$\frac{1}{\lambda^2} = \frac{1}{D_+ \tau_{+-}} + \frac{1}{D_- \tau_{+-}}. \quad (5)$$

In a one-dimensional device structure, it is more convenient in algebra to use the current instead of its density.

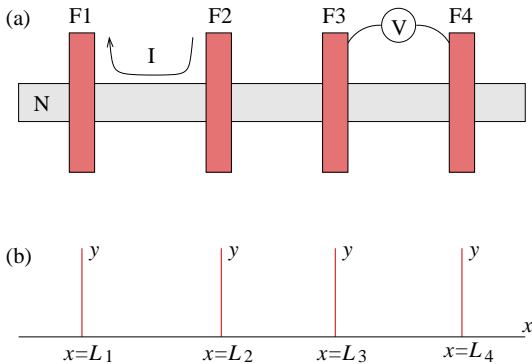


FIG. 1: Schematic display of the lateral spin valve system with four ferromagnetic electrodes. (a) Ferromagnetic electrodes are labeled as F1, F2, F3, and F4 from left to right. The base electrode is denoted as N. The current I is injected from F2 into N and drained to F1. The voltage induced by the spin current is measured between F3 and F4 electrodes. (b) The one-dimensional model geometry of the spin valve system in (a).

As we shall show below, the use of properly defined material parameters highly simplifies the algebra.

We consider the model spin valve structure in Fig. 1. The spin-polarized current I flows from F2 into N and F1. The spin-dependent electrochemical potential ($\mu_{i\pm}$) and current ($I_{i\pm}$) in each FM electrode can be parameterized as

$$\frac{1}{e} \begin{pmatrix} \mu_{i+} \\ \mu_{i-} \end{pmatrix} = \left[\frac{I}{\sigma_1 A_1} y \delta_{i,1} - \frac{I}{\sigma_2 A_2} y \delta_{i,2} + U_i \right] \begin{pmatrix} 1 \\ 1 \end{pmatrix} - I_i \mathcal{R}_i e^{-y/\lambda_i} \begin{pmatrix} [1 + \beta_i]^{-1} \\ -[1 - \beta_i]^{-1} \end{pmatrix}, \quad (6)$$

$$\begin{pmatrix} I_{i+} \\ I_{i-} \end{pmatrix} = \frac{I}{2} \begin{pmatrix} 1 + \beta_1 \\ 1 - \beta_1 \end{pmatrix} \delta_{i,1} - \frac{I}{2} \begin{pmatrix} 1 + \beta_2 \\ 1 - \beta_2 \end{pmatrix} \delta_{i,2} + \frac{I_i}{2} e^{-y/\lambda_i} \begin{pmatrix} 1 \\ -1 \end{pmatrix}. \quad (7)$$

The index i runs from 1 through 4, labeling the four FM electrodes. As will be clear below, $U_i = V_i + \Delta \delta_{i,1}$ and the shift Δ is introduced to take into account the current flow in the common electrode. That is, the electrochemical potential in F1 is shifted up with respect to that in F2, F3, and F4. V_i is the voltage drops in each FM electrode F_i , which is induced by the spin accumulation and diffusion. I_i measures the spin current leaking into F_i and should be determined by the Kirchoff rules at the junctions. The spin-dependent current is determined by the equation

$$I_{i\alpha} = A_i \frac{\sigma_{i\alpha}}{e} \frac{d}{dy} \mu_{i\alpha}. \quad (8)$$

Note that the i -th FM lead is contacted to the common electrode at $x = L_i$. A_i , λ_i , σ_i , and β_i are the cross-sectional area, the spin diffusion length, the conductivity, and the bulk spin polarization in the conductivity of the i -th FM lead, respectively. \mathcal{R}_i is the resistance of the FM lead over the spin diffusion length and is defined by the relation

$$\mathcal{R}_i = \frac{\lambda_i}{\sigma_i A_i}. \quad (9)$$

The spin-dependent conductivity $\sigma_{i\pm}$ can be written in terms of the spin polarization β_i as

$$\sigma_{i\pm} = \frac{1}{2} \sigma_i (1 \pm \beta_i). \quad (10)$$

In the common base electrode, the spin-dependent electrochemical potential (μ_\pm) and current (I_\pm) can be writ-

ten as

$$\begin{aligned} \frac{1}{e} \begin{pmatrix} \mu_+ \\ \mu_- \end{pmatrix} &= - \sum_i J_i \mathcal{R} e^{-|x-L_i|/\lambda} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \\ &\quad - \frac{I}{\sigma A} (x - L_2) \begin{pmatrix} 1 \\ 1 \end{pmatrix} \theta(x - L_1) \theta(L_2 - x) \\ &\quad + \frac{I}{\sigma A} (L_2 - L_1) \begin{pmatrix} 1 \\ 1 \end{pmatrix} \theta(L_1 - x), \end{aligned} \quad (11)$$

$$\begin{aligned} \begin{pmatrix} I_+ \\ I_- \end{pmatrix} &= - \frac{I}{2} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \theta(x - L_1) \theta(L_2 - x) \\ &\quad + \frac{1}{2} \sum_i J_i \text{sgn}(x - L_i) e^{-|x-L_i|/\lambda} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \end{aligned} \quad (12)$$

Note that the electrochemical potential shift, Δ , is defined by the relation

$$\Delta = \frac{I}{\sigma A} (L_2 - L_1). \quad (13)$$

Due to the current flow between F1 and F2, the electrochemical potential is shifted up in the region $x \leq L_1$ with respect to the region $x \geq L_2$. The spin-dependent current is determined by the equation

$$I_\alpha = A \frac{\sigma_\alpha}{e} \frac{d}{dx} \mu_\alpha, \quad \sigma_\alpha = \frac{\sigma}{2}. \quad (14)$$

A , λ , and σ are the cross-sectional area, the spin diffusion length, and the conductivity of the base electrode N, respectively. $\mathcal{R} = \lambda/\sigma A$ is the resistance of the base electrode, which is defined over the spin diffusion length of the base electrode.

There are three sets of unknown parameters, V_i , I_i , and J_i 's, which we are going to determine by using the boundary conditions or the Kirchhoff rules at the junctions. The above expressions of the electrochemical potential are constructed such that the charge current at each junction is conserved and flows from the F2 lead into the common base electrode and finally into the F1 lead. Though the spin-flip scattering in the bulk is taken into account, any possible spin-flip scattering at the interface between the FM leads and the nonmagnetic base electrode is neglected. In this case, the spin current ($I_s = I_+ - I_-$) is also conserved at each junction and leads to the following constraint:

$$J_i = -\frac{1}{2} I_i - \frac{1}{2} \beta_1 I \delta_{i,1} + \frac{1}{2} \beta_2 I \delta_{i,2}. \quad (15)$$

The electrochemical potential for each spin direction should satisfy Ohm's law at the junctions. At the i -th junction, the drop in the electrochemical potential is given by the expression

$$\begin{aligned} \frac{1}{e} \Delta \mu_{i\pm} &= U_i \mp \frac{\mathcal{R}_i}{1 \pm \beta_i} I_i - \left[\mp \mathcal{R} \sum_{ij} A_{ij} J_j + \Delta \delta_{i,1} \right] \\ &= V_i \mp \frac{\mathcal{R}_i}{1 \pm \beta_i} I_i \pm \mathcal{R} \sum_{ij} A_{ij} J_j, \\ A_{ij} &\equiv e^{-|L_i - L_j|/\lambda}. \end{aligned} \quad (16)$$

Ohm's law at the junctions gives the following relation:

$$\frac{1}{e} \Delta \mu_{i\pm} = \mathcal{R}_{ti\pm} I_{i\pm}, \quad (17)$$

where $\mathcal{R}_{ti\pm}$ is the spin-dependent junction resistance at the interface between the base electrode and the i -th FM electrode Fi , and can be defined in terms of the spin polarization γ_i of the junction resistance as

$$\mathcal{R}_{ti\pm} = \frac{2\mathcal{R}_{ti}}{1 \pm \gamma_i}. \quad (18)$$

$I_{i\pm}$ is the spin-dependent current passing through the i -th junction:

$$I_{i\pm} = \frac{I}{2} (1 \pm \beta_1) \delta_{i,1} - \frac{I}{2} (1 \pm \beta_2) \delta_{i,2} \pm \frac{I_i}{2}. \quad (19)$$

In our work, two types of spin polarization are introduced. One is β_i , measuring the spin polarization in the bulk conductivity in the FM electrode Fi . The other one is γ_i , which measures the spin polarization in the spin-dependent junction resistance between N and Fi . In our convention, β and γ are positive when spin-up electrons are in the majority band while they are negative when the magnetization orientation is reversed or the spin-up electrons are in the minority band.

For the algebraic manipulation, it is more convenient to introduce new parameters for the resistance:

$$R_i = \frac{\mathcal{R}_i}{1 - \beta_i^2}, \quad R_{ti} = \frac{\mathcal{R}_{ti}}{1 - \gamma_i^2}, \quad (20)$$

and $R = \mathcal{R}$. With these new notations, we have

$$\begin{aligned} V_i &= \pm (1 \mp \beta_i) I_i R_i \mp R \sum_j A_{ij} J_j \\ &\quad + R_{ti} (1 \mp \gamma_i) [I (1 \pm \beta_1) \delta_{i,1} - I (1 \pm \beta_2) \delta_{i,2} \pm I_i] \end{aligned} \quad (21)$$

Adding and subtracting the two equations, we find

$$\begin{aligned} V_i &= -(\gamma_i R_{ti} + \beta_i R_i) I_i + (1 - \beta_1 \gamma_1) R_{t1} I \delta_{i,1} \\ &\quad - (1 - \beta_2 \gamma_2) R_{t2} I \delta_{i,2}, \end{aligned} \quad (22)$$

and

$$\begin{aligned} (R_i + R_{ti}) I_i - R \sum_j A_{ij} J_j \\ = -(\beta_1 - \gamma_1) R_{t1} I \delta_{i,1} + (\beta_2 - \gamma_2) R_{t2} I \delta_{i,2} \end{aligned} \quad (23)$$

For the algebraic manipulation, it is much more convenient to use the vector and matrix notations to rewrite the equations obtained from the boundary conditions as

$$\begin{aligned} |V\rangle &= -(\hat{\gamma} \mathbf{R}_t + \hat{\beta} \mathbf{R}) |I\rangle + (1 - \beta_1 \gamma_1) R_{t1} I |1\rangle \\ &\quad - (1 - \beta_2 \gamma_2) R_{t2} I |2\rangle, \end{aligned} \quad (24)$$

$$|I\rangle = -2|J\rangle - \beta_1 I |1\rangle + \beta_2 I |2\rangle, \quad (25)$$

and

$$\begin{aligned} (\mathbf{R} + \mathbf{R}_t) |I\rangle &= -R \mathbf{A} |J\rangle \\ &= -(\beta_1 - \gamma_1) R_{t1} I |1\rangle + (\beta_2 - \gamma_2) R_{t2} I |2\rangle \end{aligned} \quad (26)$$

\mathbf{R} and \mathbf{R}_t are diagonal matrices with their diagonal elements $R_{ii} = R_i$ and $R_{tii} = R_{ti}$, respectively. We used the vector notations, for example, $\langle I \rangle = (I_1, I_2, I_3, I_4)$ and $\langle 1 \rangle = (1, 0, 0, 0)$. After some algebra, we find the expression of the desired electrochemical potential drops:

$$\frac{V_i}{I} = (-1)^{i+1}(R_{ti} + \beta_i^2 R_i)\delta_{i \leq 2} + \sum_{j=1}^2 (\gamma_i R_{ti} + \beta_i R_i) G_{ij} (-1)^j (\gamma_j R_{tj} + \beta_j R_j) \quad (27)$$

where the matrix \mathbf{G} is defined by the relation

$$\mathbf{G} = \left[\mathbf{R} + \mathbf{R}_t + \frac{1}{2} \mathbf{R} \mathbf{A} \right]^{-1}. \quad (28)$$

Note that the matrix \mathbf{G} has the dimension of conductance and is independent of the magnetization configurations in the FM electrodes. The spin current I_i is also obtained as

$$\frac{I_i}{I} = -\beta_1 \delta_{i1} + \beta_2 \delta_{i2} + G_{i1} (\beta_1 R_1 + \gamma_1 R_{t1}) - G_{i2} (\beta_2 R_2 + \gamma_2 R_{t2}). \quad (29)$$

I_3 and I_4 measure the leakage spin currents into F3 and F4, respectively. Since G_{ij} is independent of the magnetization configurations, the signs and the magnitudes of the leaking spin currents do not depend on the magnetization orientations of the F3 and the F4 electrodes (parallel or antiparallel relative to F1 and F2), but depend on those of F1 and F2. On the other hand, the voltage drops V_3 and V_4 change their sign when their magnetizations are reversed.

III. RESULTS AND DISCUSSION

In the previous section, we derived the voltage drops and leaking spin currents in the voltage probes F3 and F4. We can consider several different measurement geometries from our analytic solutions.

For the voltage probes F3 and F4, we have the spin leakage currents and the corresponding voltage drops from Eqs. (27) and (29):

$$\frac{I_i}{I} = G_{i1} (\beta_1 R_1 + \gamma_1 R_{t1}) - G_{i2} (\beta_2 R_2 + \gamma_2 R_{t2}), \quad (30)$$

$$V_i = -(\gamma_i R_{ti} + \beta_i R_i) I_i. \quad (31)$$

Note that the nonlocal voltage drop can be expressed as the product of the leakage spin current and the appropriately defined spin resistance. This spin resistance depends on the orientation of the magnetization. Our general results can be reduced to the simpler ones. When F1 is located very far away from F2 or when the distance between F1 and F2 or $|L_2 - L_1|$ is much longer than the SDL of the nonmagnetic electrode, our spin valve structure is reduced to that studied by the authors in Ref. 19, where the effect of an additional FM electrode on the nonlocal spin signals was studied. Furthermore, if the distance between F3 and F4 is much longer than the spin diffusion length, our model spin valve is reduced to the *conventional* spin valve studied in Ref. 10.

The nonlocal spin signal in the model spin valve in Fig. 1 is quantified by measuring the voltage difference between two FM electrodes, F3 and F4. Hence $\Delta V = V_3 - V_4$ is the experimentally relevant quantity and the nonlocal spin signal is defined as $R_s = \Delta V / I$, where

$$R_s = \sum_{i=3,4} \sum_{j=1,2} (-1)^{i+j+1} (\gamma_i R_{ti} + \beta_i R_i) G_{ij} \times (\gamma_j R_{tj} + \beta_j R_j). \quad (32)$$

This is the main result of our work.

To get some insight about the nonlocal spin signal R_s , let us start with an algebraic manipulation of the conductance matrix \mathbf{G} . For the calculation of the inverse matrix G , we note the symmetry of G and G^{-1} can be rewritten as

$$G^{-1} = \begin{pmatrix} A & T \\ T^\dagger & B \end{pmatrix}, \quad (33)$$

$$A = \begin{pmatrix} r_1 & \frac{1}{2} f_1 R \\ \frac{1}{2} f_1 R & r_2 \end{pmatrix}, \quad (34)$$

$$B = \begin{pmatrix} r_3 & \frac{1}{2} f_3 R \\ \frac{1}{2} f_3 R & r_4 \end{pmatrix}, \quad (35)$$

$$T = \frac{1}{2} f_2 R \begin{pmatrix} f_1 & f_1 f_3 \\ 1 & f_3 \end{pmatrix}. \quad (36)$$

Here, $f_i = e^{-|L_{i+1} - L_i|/\lambda}$ with $i = 1, 2, 3$, and $r_i = R_i + R_{ti} + \frac{1}{2} R$ with $i = 1, 2, 3, 4$. The 2×2 matrix T is real, and its hermitian T^\dagger is equivalent to its transpose T^t . Though $|T| = 0$, the determinants of A and B are nonzero so that we can find the conductance matrix G in a manageable form. The inverse of a 4×4 matrix is reduced to that of 2×2 matrices, which is much simpler to compute:

$$G = \begin{pmatrix} A^{-1}[1 - TB^{-1}T^\dagger A^{-1}]^{-1} & -A^{-1}TB^{-1}[1 - T^\dagger A^{-1}TB^{-1}]^{-1} \\ -B^{-1}T^\dagger A^{-1}[1 - TB^{-1}T^\dagger A^{-1}]^{-1} & B^{-1}[1 - T^\dagger A^{-1}TB^{-1}]^{-1} \end{pmatrix}. \quad (37)$$

For the nonlocal spin signals such as I_3, I_4 and V_3, V_4 , only the off-diagonal block matrix is relevant. Since T contains the exponentially decaying factor with the scale of the spin diffusion length, we may approximate the matrix G in the

expression of a nonlocal spin signal as

$$\begin{aligned} \begin{pmatrix} G_{31} & G_{32} \\ G_{41} & G_{42} \end{pmatrix} &= -B^{-1}T^\dagger A^{-1}[1 - TB^{-1}T^\dagger A^{-1}]^{-1} \approx -B^{-1}T^\dagger A^{-1} \\ &= -\frac{f_2 R}{2(r_1 r_2 - \frac{1}{4}f_1^2 R^2)(r_3 r_4 - \frac{1}{4}f_3^2 R^2)} \begin{pmatrix} f_1(r_2 - \frac{R}{2})(r_4 - \frac{1}{2}f_3^2 R) & (r_1 - \frac{1}{2}f_1^2 R)(r_4 - \frac{1}{2}f_3^2 R) \\ f_1 f_3(r_2 - \frac{1}{2}R)(r_3 - \frac{1}{2}R) & f_3(r_1 - \frac{1}{2}f_1^2 R)(r_3 - \frac{1}{2}R) \end{pmatrix}. \end{aligned} \quad (38)$$

This approximate form is valid when the distance between the current probe F2 and the voltage probe F3 is much larger than the SDL so that the matrix T is small. For a more accurate calculation, the exact form of the conductance matrix \mathbf{G} is needed. However, the above approximate conductance matrix is enough to get some insight into the nonlocal spin signal R_s .

Since f_i is an exponentially decaying factor over the spin diffusion length, the most dominant contribution in the nonlocal spin signal R_s comes from G_{32} . The nonlocal spin signal or the transresistance R_s in Eq. (32) can be rewritten in decreasing order as

$$\begin{aligned} R_s &= (\gamma_3 R_{t3} + \beta_3 R_3)G_{32}(\gamma_2 R_{t2} + \beta_2 R_2) \\ &\quad - (\gamma_3 R_{t3} + \beta_3 R_3)G_{31}(\gamma_1 R_{t1} + \beta_1 R_1) \\ &\quad - (\gamma_4 R_{t4} + \beta_4 R_4)G_{42}(\gamma_2 R_{t2} + \beta_2 R_2) \\ &\quad + (\gamma_4 R_{t4} + \beta_4 R_4)G_{41}(\gamma_1 R_{t1} + \beta_1 R_1). \end{aligned} \quad (39)$$

Due to the exponential factors, the first line is dominant and the last line is the weakest. Obviously, the nonlocal spin signal will change its sign when the magnetization orientation of two neighboring FM electrodes F2 and F3 is inverted.

In experiments, the magnetic configurations are scanned by sweeping the external magnetic field along the geometrically parallel FM electrodes. With different widths of the FM electrodes, the coercive fields are different due to the different strengths of an easy axis anisotropy along the electrode direction. Starting from a large negative field, all the FM electrodes are aligned with the magnetic field. As the magnetic field is swept from negative to positive, the FM electrodes reverse their magnetization one by one when the magnetic field equals their coercive field. While sweeping the magnetic field from large negative to large positive, we have four different magnetization configurations so that nonlocal spin signal will show four different states. When the magnetic field is now swept from large positive to large negative, we have again four different magnetization configurations. Under the time reversal operation or when the magneti-

zation orientation of all four FM electrodes is reversed, we can readily see that the nonlocal spin signal R_s does not change its sign. This means that there are only four different values of R_s under the magnetic field sweeping. In principle, there can be 4 different states in the nonlocal spin signal, depending on the relative orientations of magnetizations. However, the number of actual states realized in experiments may well depend on the distance between the FM contacts, the relative magnitudes of the spin resistances in R_s . We note that all four states were observed in Ref. 20 for a nonlocal spin valve with Al as a base electrode, three states in Ref. 14, and two states in Ref. 13.

IV. SUMMARY AND CONCLUSION

In this paper, we studied the nonlocal spin transport in a lateral spin valve with four FM electrodes, out of which two are used as current injectors and the other two are used as spin current detectors or the voltage probes. We calculated the general expressions for the nonlocal signals, such as the leakage spin current and the voltage drop due to the spin accumulation. Since there are four ferromagnetic electrodes in our model spin valve structure, in principle, four different nonlocal spin signal states are possible. In real experiments, the number of observed states is found to depend on the inter-electrode distance, the relative magnitude of spin resistances.

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